# Joint Centre for Mesoscale Meteorology, Reading, UK

## An Appreciation of the Meteorological Research of Ernst Kleinschmidt

A. J. Thorpe

Internal Report No. 11

May 1992

**Met Office** Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com

*Designed and produced by the Met Office © Crown copyright 2001 01/0240 The Met Office logo is a registered trademark.*

# An Appreciation of the Meteorological Research of Ernst Kleinschmidt

Alan J Thorpe
Department of Meteorology, University of Reading, England

13 May 1992

## Abstract

Much of the pioneering work in interpreting atmospheric dynamics in terms of potential vorticity (PV) was carried out in the early 1950's. The realisation that PV is conserved under certain conditions was made earlier by Ertel and Rossby but its use in theorizing largely comes from the work of Ernst Kleinschmidt. Recent mention of his work has been made by Hoskins, McIntyre, and Robertson (1985) but here we present a more comprehensive and detailed account of the various contributions made by Kleinschmidt to this subject.

In a body of work amounting to 17 published papers he addressed the following problems: the nature of symmetric instability (dry and moist); a theory and observational analysis of mid-latitude cyclogenesis in terms of the producing mass concept (including the recently-named invertibility principle); a theory of the development and dynamics of tropical cyclones; and an observational analysis concerning ageostrophic winds in the upper troposphere.

The aim here is to review this research, most of which was published in German language papers, to place it in its historical context.

## 1 Introduction

The contributions of the German meteorologist Ernst Kleinschmidt, particularly in the field of dynamics and the cyclone problem, are lately being recognized. The aim of this paper is to present a brief review of these contributions in order to expose some of the important aspects of these works in the context of the modern viewpoint in these areas of meteorology.

The following description of Kleinschmidt's research is divided into that on extratropical cyclones, tropical cyclones, and ageostrophic wind-fields. There are other topics considered in his publications but in the interests of brevity we focus on these areas. It should be noted that the references in this paper are divided into numbered contributions from Kleinschmidt and those related papers by other authors. Kleinschmidt's papers will be referred to by their number whereas the others will be referenced in the usual way. In quotations from his papers the original notation

and terminology will be preserved. Thus Kleinschmidt uses Z for potential vorticity which is otherwise herein denote by PV. The term "dynamical instability" is now generally replaced by "symmetric instability"; the reason for this change in terminology is discussed in section 3. The supporting bibliography is not complete as this is not intended to be a comprehensive review of these subjects; they rather point to some of the contemporary research following on from that of Kleinschmidt.

A list of acknowledgements to scientists who have assisted me in putting this paper together is given at the end but special thanks go here to Dr. Christa Kleinschmidt, Ernst's wife, who most charmingly encouraged this enterprise.

## 2 Biographical summary

Ernst Kleinschmidt was born in Germany on 20 December 1912 the son of an eminent German meteorologist. His undergraduate university education was in mathematics and physics and he obtained a PhD in meteorology under Professor Raethjen's supervision at the University of Hamburg in 1941. Raethjen apparently regarded Kleinschmidt as his best student and gives fulsome praise of his contributions in his book "Dynamik der Zyklonen", published in 1953, putting them alongside those of Rossby. During the war Kleinschmidt was in the Weather Observer Corps of the 2nd Air Fleet Command and travelled extensively. In 1946 he joined the Kaiser Wilhelm Institut für Strömungsforschung (flow research) in Göttingen where he stayed until his death on 4 May 1971. This institute is an illustrious one having been set-up in 1925 with Professor Prandtl as its head. In 1946 Prandtl, aged 71, retired as institute director and in 1948 it was renamed the Max Planck Institut für Strömungsforschung. Tollmien came to the Max Planck Institut at this time. In the early years after the war Kleinschmidt was an assistant to Prandtl. As research on aerodynamics was forbidden Prandtl decided to pursue research in the more "neutral" field of meteorology.

Kleinschmidt made two scientific visits abroad on invitations from Rossby in 1951 to the University of Stockholm and from Riehl in 1959/60 to the University of Chicago. The former was an attempt by Rossby to bring together scientists from both war camps. Ernst Kleinschmidt's wife Christa, who was also a meteorologist and attended Rossby's conference, recounts that Rossby "....thought of him as an artist because of his imaginiative ability". Arnt Eliassen remembers with some regret that Kleinschmidt's lectures in Stockholm were regarded as somewhat queer and were not taken too seriously.

It is clear that Kleinschmidt's latter years were darkened by depression and loneliness not least because of the adverse reaction to his research of that later period on ageostrophic wind-fields. Professor Tollmien did not allow Kleinshmidt to pursue this work contrary, as it was, to the accepted view.

# 3 Extratropical cyclones

## 3.1 Symmetric instability

The first two papers of Kleinschmidt (1 and 2) describe his PhD thesis work on dynamical instability. This topic was one which was of considerable interest at that time having been considered by Helmholtz (1888) and Solberg (1928) as an explanation for cyclone development; the latter paper was not referenced by Kleinschmidt. The use of the term dynamical is to distinguish this from static instability. At that time baroclinic instability had not been discovered but following its introduction the term symmetric, rather than dynamical, is now used. This is because the theoretical description of dynamical instability is of a two-dimensional baroclinic type mode; with other instabilities being discovered the term dynamical is clearly too broad.

A simplified stability analysis is presented in (1) giving the criterion for this two-dimensional instability to be that the isentropic absolute vorticity should be negative. The analysis is different from that of Helmholtz and more general in applying to a continuously varying fluid rather than only to a 2-fluid layer model. It appears to be a simplified form of the parcel model introduced by Solberg (1928). A discussion follows about the possible geographical variations in the instability, the extension to saturated flow by using $\theta_e$ surfaces, and the possibility of a moist neutral condition applying at fronts. Also the mechanism of destabilizing the atmosphere is discussed. One is left with the feeling that this is a theory waiting for a proper application to the atmosphere by making a detailed synoptic data analysis. This was to come after the war when Kleinschmidt began work in Prandtl's laboratory. The complete mathematical description of moist or conditional symmetric instability awaited the work of Bennetts and Hoskins (1979), although in the intervening years several authors (including most notably Sawyer) considered the topic of some importance in describing frontal structure.

## 3.2 Tropopause cyclones

In a three part paper entitled "On the structure and origin of cyclones" (3, 4 and 5) Kleinschmidt explored how PV concepts could be used to construct a paradigm concerning extratropical cyclones. It should be remembered that at that time, following the Bergen school's identification of cyclone families on the so-called polar front, the hunt was on for a convincing theoretical explanation for the formation of such wave or frontal cyclones. Baroclinic wave theory in the form of a linear normal mode instability had been described in publications by Charney (1947) and Eady (1949). These papers are not referred to by Kleinschmidt so we do not know whether he was unaware of their existence (probably unlikely) or felt them to be irrelevant to the approach he was taking. The latter view is defensible as Kleinschmidt's approach has similarities to that of the Norwegians in developing ideas from synoptic case studies rather than that of the mathematical fluid dynamics approach of Charney and Eady. Furthermore his model was inherently finite amplitude in nature in that it considers the processes maintaining a cyclone rather than conceiving of a, hypothetical, basic flow which might exhibit growth of infinitesimal perturbations.

In part 1 (3) Kleinschmidt looks at a cyclone, which to modern eyes is not a very remarkable one, which developed over a 12 hr period on 6 March 1943 to give more precipitation than seemed likely from its previous history. From routine radiosounding data he notes the existence of ".... a lentiform mass, differing from the surrounding masses by a very different gradient of $\theta$, settled between the troposphere and stratosphere to the west of the ground cyclone. This body or 'Höhenkörper' is the primary object of our investigation". We reproduce his figures 2 and 4 as our figure 1. The Höhenkörper can be followed for 36 hr and Kleinschmidt goes on to state that "There is no doubt that the body was the cause of the further development of the low ...It drifts along from the north-west, almost catches up with the depression but then turns off southwards to the Mediterranean, while the low continue on its way ESE". He claims that the body then comes over another depression in the western Mediterranean which then begins to develop anew. It is interesting to note that this remark is of some importance since an upper-level PV-streamer stretching southward towards the Alps is now regarded as a significant feature of Alpine lee-cyclogenesis (Bleck and Mattocks (1984), Tafferner (1991), Pichler et al (1990), and Volkert et al (1991)). In summary, Kleinschmidt says that ".... the body has nothing to do with the surface depression. It is an independent formation, drifting along with the general high altitude current and ...wherever it arrives it disrupts the existing situation".

This description has similarities to the type-B cyclogenesis events proposed by Petterssen and Smebye (1971). On the basis of numerous synoptic analyses of cyclogenesis these authors classified two types of development. Type-B essentially relies on the progression of an upper level trough to initiate and promote cyclogenesis. Kleinschmidt was not the only scientist to use potential vorticity in synoptic anaysis in the 1950's. Reed (1955) made extensive use of it in discussing upper frontogenesis. Later Danielsen (1968) interpreted tropspheric-stratospheric exchange in terms of potential vorticity. More recently Shapiro (1976 for example) has also discussed observations of the potential vorticity structure of tropopause disturbances whilst Lanzinger et al (1991) show maps of potential vorticity on isentropic surfaces in the ALPEX-Atlas.

The next part of that paper (3) presents a theoretical model of the atmosphere including this lentiform body. The important initial step is to identify the region of higher static stability with the more general concept of potential vorticity. This quantity is introduced by reference to Ertel and its properties as an air-mass tracer in the absence of frictional or diabatic processes are noted. The model involves prescribing the PV distribution in a circular region and finding and solving equations for the consistent gradient wind flow and temperature fields. This process has been called the "invertibility principle" by Hoskins et al (1985). Kleinschmidt states that ".....the model.....is less a matter of reproducing reality than of presenting a vivid example which might clearly demonstrate some basic facts". The distribution of PV used is very interesting with a uniform value of 0.3 PVU in the bulk of the troposphere, 2.4 PVU in the stratosphere, and in the lens in the upper troposphere values rising to 1.5 PVU at its centre. (note that 1 PVU $=10^{-6} Km^2 s^{-1} kg^{-1}$). This distribution is shown in figure 2 (which reproduces figure 8 of (3)). There is a peak of PV in the core of the cyclone in the "troposphere" at about 9 km decreasing slightly before stratospheric values are reached at about 13 km. The solution of the inversion equation given on the right-hand-side of the figure for the wind speed and temperature is approximate as

he describes various approximations to allow analytical solution in the form of Bessel functions. Numerical solutions of the exact inversion equation are given in Thorpe (1986) for somewhat simpler PV distributions.

The realism of the cyclonic vorticity, surface pressure, and winds of the balanced vortex solution suggests that "A cyclone (or an anticyclone) can only exist if it contains masses with an anomalous Z, i.e. if the function Z ($\theta$) on a vertical line in the interior of the cyclone has other values than those outside". This is elevated to the status of a theorem "... at some altitude within a cyclone there must be masses with excessive values of Z and in an anticyclone there must be masses with a low Z". The paper closes with the only question left namely what is the origin of the anomalous PV? He lists the two possibilities of advection or "..... the cyclone body is newly created during the cyclogenesis .... which can only happen by a non-adiabatic process".

These ideas are interesting from two viewpoints aside from the general importance of the invertibility principle that is postulated. It is clear that even if Kleinschmidt had read Eady or Charney's work he did not appreciate the importance of surface baroclinicity to cyclone development. All the PV inversions done in (3) take zero surface baroclinicity. Following the work of Bretherton (1966) such temperature gradients can be thought of as surrogate anomalous PV. In fact the Eady model, for example, was not originally couched in terms of PV but we now recognize that such baroclinic instability can even occur in an atmosphere with uniform PV but with baroclinicity at the ground and at the tropopause phase-locked (see Hoskins et al. 1985). This is not to say that that is the way cyclones in the atmosphere develop and it is still an open question as to the relative importance in observed cyclones of boundary thermal gradients as opposed to anomalous PV as imagined by Kleinschmidt.

The second aspect of interest is the notion of a body in the upper troposphere of distinct PV with a value intermediate between typical tropospheric and stratospheric values. This does not accord with the general view held now that in fact type-B cyclogenesis is associated with an upper trough or local depression of the tropopause. In the modern view we would probably cast doubt on whether observational errors in analysing PV were such that Kleinschmidt's intermediate values of PV were in fact really stratospheric values. However it is the belief of the author that insufficient high-quality analyses of PV in the troposphere have been made to identify whether intermediate masses, such as those described by Kleinschmidt, exist or not. Perhaps this is still a hypothesis which needs to be assessed as analysis methods improve. It is interesting that in the later summary of these ideas in the review with Eliassen (10) a much clearer mathematical formulation is given and a solution is presented for a lentiform body with uniform PV of 6 times the background tropospheric value but which is still separated from the stratosphere. Despite this separation these cyclones are referred to in (10) as tropopause cyclones and the existence of a distinct tropospheric anomaly is downplayed compared to that which is produced by a deformed tropopause geometry. The idea in (10) that these tropopause cyclones appear "...closely connected with the upper-air flow pattern" even more emphasises the similarity with the type-B cyclogenesis postulated later by Petterson and Smebye (1971).

In the third part of the paper (6) the origin of increased PV at various levels is pursued in another case study of 17 December 1949. The analysis presents calculations

of isentropic distributions of PV on the 338, 308, and 288 K surfaces at 12 hr intervals over a 24 hr period. The advective origin of an upper level PV maximum is described. The origin of the structure of the PV field at lower levels is the subject of the second part of the paper (4) on frontal cyclones.

## 3.3 Frontal cyclones

In the second part of his set of papers on the origin and structure of cyclones (4) Kleinschmidt pursues the mechanism by which an air-mass can acquire anomalously large PV and thus create a cyclone. (Note that this paper also forms the basis of the description in (10) of frontal cyclones). This is done using another case study of a cyclone or rather the family of cyclones of 16 November 1943 occurring over central Europe. In the introduction he says that "We shall see that it is the condensation process connected with the frontal wave, the so-called upgliding rain (Aufgleitregen) which creates the body of the cyclones". As already described the term "body" refers to an air-mass with anomalous PV. In (10) the word "body" is replaced by "producing mass" in the sense of the mass of high PV which is responsible for producing the cyclone. The synoptic analysis shows a polar front stretching from north-eastern Russia to the central Mediterranean along which 3 frontal cyclones develop. Kleinschmidt concentrates on one of these three developments.

In figure 3 we reproduce figure 3 of (4), which is a vertical cross-section through the warm-front of the cyclone. It is a triumph of draughtsmanship as well as of synoptic analysis. The theory is in two parts which are not clearly separated from one another. The first is the notion that the growth of the frontal cyclone is due to moist dynamic instability and the second is that PV is increased in the lower troposphere and decreased in the upper troposphere due to latent heat release. Both of these mechanisms are invoked for the development of the cyclone. It seems, but it is difficult to be certain, that Kleinschmidt had in mind a two stage process in which moist symmetric instability is the cause of the earliest growth whereas the PV anomalies are fundamental in maintaining the cyclone.

In figure 3 there is clear evidence of the vorticity vector lying parallel to the $\theta_e$ lines which is the neutral condition for moist symmetric instability. Kleinschmidt seems to regard this feature as indicative of actual instability. Considerable emphasis has been placed recently on the neutral condition in frontal zones by Emanuel (1985) and on actual instability by Sanders and Bosart (1985); the issue of whether there is actual moist symmetric instability or merely a tendency to approach neutral conditions from the stable side is still an important and unresolved one. It seems likely that Kleinschmidt uses the existence of the neutral condition in the developed cyclone as a proxy indication of previously existing unstable conditions in the cyclone growth phase. As part of his discussion on symmetric instability Kleinschmidt notes that the criterion for the instability is that the PV must be negative; this was independently deduced later by Hoskins (1974).

Kleinschmidt then suggests that at a local zone along a quasi two-dimensional front a cloud forms due to moist symmetric instability. Neighbouring regions of the front remain unsaturated thus providing the local spin-up of the nascent cyclone. Of course the theory of conditional symmetric instability relates to a strictly two-dimensional

flow and cloud , see Bennetts and Hoskins (1979). The notion of this instability occuring in an essentially three-dimensional form awaits a theoretical justification.

As Kleinschmidt puts it "We now ... tackle the real problem, namely the origin of the cyclone body. To anticipate the solution: in the masses of the lower tropospheric flow Z is greatly increased during its passage through the rain zone". It is interesting to note that in the later review article with Eliassen (10) the emphasis on moist symmetric instability as the causative mechanism is much reduced and the creation of the producing mass of high PV is advanced as the primary mechanism. The analysis proceeds by constructing, on the basis of an assumption of steady flow, 5 trajectories through the cyclone. From this the substantially different three-dimensional flow of air through the cyclone at upper and lower levels is identified. No attempt is made to diagnose the PV itself from the observations; rather its rate of change along trajectories due to latent heat release is calculated. To compute the latent heat release the vertical velocity is estimated from the horizontal winds and the slope of the $\theta_e$ lines. Kleinschmidt deduces that the PV should increase by 1.1 PVU on a parcel during its ascent from the surface to a height of 3.3 km along the frontal surface. Hence he proposes that we should expect to see a PV value in the lower troposphere of 2 to 3 times the surrounding value. In the third part of this paper (6) he presents the distribution of potential vorticity on the 288 K isentropic surface for a different synoptic case; indeed there is a ribbon of high values in the warm frontal region at these low levels. That this distribution is commonplace is lent credence from recent analyses of PV using synoptic observations at cold fronts by Hoskins and Berrisford (1988) and by Joly and Thorpe (1990).

In the upper troposphere Kleinschmidt notes that "The increase in Z in the lower flow and the formation of the cyclone body are only one half of the condensation effect.... the upper flow suffers a decrease in Z when it traverses the condensation area..... the reduced Z in the upper flow leads to the building up of an anticyclone in the area ahead of the frontal wave". This description anticipates the later proof that the decrease in Z must exactly equal the increase in Z as a mass-weighted volume integral, Thorpe and Emanuel (1985). The mean vertical shear of the frontal zone is invoked to allow a horizontal separation of the lower cyclone and upper anticyclone. This separation is crucial because if "....cyclonic and anticyclonic masses are above one another they cancel themselves out .....the gradient wind achieves a speed of only a few m/s. It is only when the parts are separated that they achieve their full effect and demand wind fields with considerable energy".

There is little doubt that this description is more akin to type-A cyclogenesis as classified by Petterssen and Smebye (1971). Type-A is the development of a cyclone on a, possibly broad, baroclinic zone without the support of an upper-level disturbance. An attempt to put mathematical substance into Kleinschmidt's model has recently been made by Joly and Thorpe (1990 and 1991). More detailed synoptic and mesoscale analysis of field observations is needed to clarify which of these mechanisms is the more commonplace.

In a postscript to this work Kleinschmidt returned to the topic in the last paper he published in 1969 (17) with G-M Peter. The theme is much the same and it acts as a useful summary here to quote the abstract of that paper: "According to simple theoretical considerations it is a necessary and sufficient condition for cyclogenesis

that, in a completely bounded airmass, the potential vorticity increases. In the particular case studied here one finds that in the central part of the cyclone the potential vorticity increases greatly. Everything indicates that this increase is due to the condensation of water vapor in the region of upgliding motion. For a tropopause funnel developing in connection with the surface cyclone the analysis shows that its origin is at least partly due to diabatic cooling in the middle troposphere".

Nothing is said by Kleinschmidt about the formation of the front itself. In common with the Norwegians he considers the main problem to be to explain the development of the cyclones. The evolution of a distinct warm and cold front in the nascent frontal cyclone is described by Kleinschmidt as being a consequence of the air-flow curvature consistent with the development of the PV structure. Note that the PV also plays a central role in the semi-geostrophic theory of frontogenesis and cyclogenesis (Hoskins and Bretherton, 1972 and Hoskins, 1982). There the baroclinic wave develops into a mature cyclone in semi-geostrophic simulations using the constraint of uniform tropospheric PV (Hoskins and West, 1979 and Schär, 1989). Inevitable in such cyclone evolution is the formation of cold and warm fronts. The role of non-uniform PV, generated by condensation, at idealised fronts has been discussed recently by Emanuel et al (1987) in the context of the semi-geostrophic formulation.

# 4 Tropical cyclones

In contrast to his work on extratropical cyclones Kleinschmidt published only one paper on tropical cyclones (7). This is also the only paper which attempts a more-or-less complete mathematical theory. It has not been extensively quoted in the review literature on tropical cyclones but part of it does form the basis of the description of tropical cyclone structure given in Palmén and Newton (1969). The model is in two parts, the first is a theory of the initial growth and the second describes the steady state mature cyclone.

As was popular then the growth phase was described as being due to dynamical moist instability; this followed on from Kleinschmidt's PhD work (1,2). This idea was not new and indeed Sawyer (1947) discusses this possibility for tropical cyclones. What distinguishes Kleinschmidt's analysis is the discussion of PV. The model is empirically based in that it takes an arbitrary but plausible radial distribution of the geopotential height contours. From this distribution and the assumption of gradient wind balance he deduces, in terms of the few parameters of that distribution, the condition for a region in the upper troposphere to be moist dynamically unstable. The moist unstable region is in the form of a ring at a height of 8 km with a width of 34 km located at 58 km from the centre of the disturbance. In summary the initiation mechanism ("What then brings about a dangerous initial situation?") is via dynamical instability.

Also the PV distribution is computed and it is noted that there is in the cyclone core a "...narrowly limited mass of high Z with focal point at a height of about 5 km and above this a rapid transition to sub-normal Z". The PV structure may arise in nature either "...if masses of high Z move to the west with the trade winds, whereas masses of low Z are stored in the weak westerly winds lying above them" or

"the effect of non-adiabatic processes; in these circumstances the widespread showers which precede the typhoon might play a role".

It is no longer in vogue to suppose that tropical cyclones grow due to dynamical instability although this is an aspect of the problem which is considered the hardest to understand and about which there is still no accepted theory. The structure of the PV described by Kleinschmidt has, however, been recently verified by analysis of observations of hurricane structure by Schubert and Hack (1983). As pointed out by Thorpe (1985) and Schubert and Alworth (1987), echoing this analysis of Kleinschmidt, the role of PV unifies the dynamics of extratropical and tropical cyclones.

The steady cyclone structure relies on the assumption, above the friction layer, of neutrality to moist symmetric displacements i.e. congruent $\theta_e$ and angular momentum surfaces. This idea has recently been re-introduced into the literature by Emanuel (1986) in an attempt to point out that tropical cyclones do not rely on tapping potential energy directly from conditional instability. We are left in no doubt about Kleinschmidt's view that "During the inflow process pseudo-potential temperature is greatly increased, on the one hand by the direct heat transfer from the water to the air, and on the other - and this is the more important process - by the evaporation of the sea-water" and that "...the air-masses, in the innermost part of the storm zone, leaving the sea-surface have almost the temperature of the water and are saturated with water vapour". The role of the underlying surface is further reinforced by the statement that "The heat removed from the sea by the storm is the basic energy source of the typhoon".

The model is then developed further by introducing a friction layer model in which the radial and tangential flow therein are given a dependence on height suggested by an analysis of Prandtl's. On the basis of a momentum budget the dependence of the tangential wind at the top of the boundary layer with radius is deduced. The model is closed by imaging a circular thermodynamic path as the air performs its radial circulation and demanding a total energy balance. From this involved analysis he concludes that "... the greatest wind strength in the typhoon depends only on the structure of the outer atmosphere and on the water temperature". An estimate is derived for the central pressure depression which for modest values of the dependent parameters is found to be 24 mb. Kleinschmidt supposes that extreme cyclones must have greater available thermodynamic energy (as measured around the circular path) than he had assumed. As regards the eye of the tropical cyclone he imagines that it comes into equilibrium with the outer circulation just determined.

In summary Kleinschmidt's model of tropical cyclone dynamics relies on moist symmetric instability for the initial development and in its mature state the cyclone is neutral in this slantwise sense with its energy source derived primarily from sea-water evaporation. This structure of the mature cyclone is very much the view emerging from recent modelling efforts such as Rotunno and Emanuel (1987). The initiation mechanism seems less realistic. The PV structure and its implications are yet to be fully exploited by modern workers. Kleinschmidt does not address asymmetrical aspects of tropical cyclones and indeed these are only recently being considered to any degree by theoreticians.

# 5 Ageostrophic wind-fields

In the most controversial research of his career Kleinschmidt postulated that there was a force missing from the equations of motion (9, 13 and 16). In an analysis of synoptic data at around the 200 mb level of trough-ridge patterns over the USA and Canada he finds there to be large ageostrophic flow components. An attempt is made to also compute the Lagrangian acceleration of air to see if these large ageostrophic winds can be accounted for quantitatively. He finds there to be a substantial discrepancy between these which leads to the idea of accounting for this by frictional forces. Kleinschmidt then uses a simple eddy viscosity term to evaluate the frictional forces; the key is then to give a value to the exchange coefficient. Only the vertical mixing term is included. He states that "Unfortunately nothing further is known about this constant in the upper troposphere. To estimate its influence, an arbitrary, but presumably excessive value was substituted, namely 30 $m^2 s^{-1}$." He finds that the frictional force cannot account for either the direction and magnitude of the discrepancy. In passing we can note that, although this is not the resolution of Kleinschmidt's discrepancy, the value of eddy viscosity he used would not now be regarded as being particularly large.

From these findings Kleinschmidt makes the astonishing conclusion that there is a missing force in the equations of motion. This was not generally well received by the German meteorological community and Kleinschmidt's research in this area was eventually forbidden by the head of the institute, Tollmien. It is unfortunate that Kleinschmidt's latter years were darkened by this negative reaction from his colleagues. This research might have been less controversial these days as we are used to the notion that the nature of the turbulent mixing in the free atmosphere and in particular at around the tropopause level is not well understood.

# 6 Final remarks

Meteorological science owes a lot to the endeavours of German scientists and Ernst Kleinschmidt should have a position alongside the best of this school. His promotion of potential vorticity concepts to explain aspects of mid-latitude and tropical cyclones in the 1950's has, 30 years later, been recognised and these are now at the heart of dynamical thinking.

# Acknowledgements

Many scientists have helped me with either personal recollections of Kleinschmidt, with dynamical ideas, or with translations and thanks are due to: S A Clough, H C Davies, J Egger, A Eliassen, K A Emanuel, G Fischer, H Fortak, L Hasse, M Holt, B J Hoskins, A Joly, C Kleinschmidt, J Kuettner, M E McIntyre, M K McVean, E A Müller, C Newton, R J Reed, and F Wippermann.

Thanks are also due to the Meteorological Office library which arranged for several of the translations to English to be made.

This paper was completed during a summer visit to DLR Oberpfaffenhofen and thanks go to them for financial support and to Ute Löb for typing the manuscript. I am especially grateful to Hans Volkert who has helped with points of translation, scientific interpretation, and encouragement.

# References

Scientific papers of Ernst Kleinschmidt:

1. 1941 a: Stabilitätstheorie des geostrophischen Windfeldes (Theory of the stability of the geostrophic wind-field). Ann. Hydr., 69, 305-325.

2. 1941 b: Zur Theorie der labilen Anordnung (On the theory of the unstable condition). Met. Zeit., 58, 157

3. 1950 a: Über Aufbau und Entstehung von Zyklonen I (On the structure and formation of cyclones). Meteorol. Rdsch. , 3, Teil 1, 1-6.

4. 1950 b: Über Aufbau und Entstehung von Zyklonen II (On the structure and formation of cyclones). Meteorol. Rdsch. , 3, Teil 2, 54-61.

5. 1950 c: Über den Aufbau atmosphärischer Druckgebilde (On the structure of atmospheric pressure systems). Ber. Dtsch. Wetterd. US-Zone Nr 12, 36-40. (Report of German Weather Service US-Zone 12).

6. 1951 a: Über Aufbau und Entstehung von Zyklonen III (On the structure and formation of cyclones).Meteorol. Rdsch. , 4, Teil 3, 89-96.

7. 1951 b: Grundlagen einer Theorie der tropischen Zyklonen (Principles of a theory of tropical cyclones). Arch. Meteorol. Geophys. Bioklimatol., 4A, 53-72.

8. 1951 c: Untersuchung eines Tropopausentrichters mit Hilfe der Ertelschen Wirbelinvarianten Z (Investigation of a tropopause funnel using Ertel's PV). Annalen der Meteorologie, 4, 131-132

9. 1955 : Die Entstehung einer Höhenzyklone über Nordamerika (The formation of a high-level cyclone over North America). Tellus, 7, 96-108.

10. 1957 : Chapters IV and V in "Dynamic Meteorology" by A. Eliassen and E. Kleinschmidt, Handbuch der Physik, 48, 112-129.

11. 1959 : Nicht-adiabatische Abkühlungen im Bereich des Jetstream (Non-adiabatic cooling in the jetstream regime). Beitr. Phys. Atmosph., 32, 94-108.

12. 1960 : An example of strong diabatic cooling over the Rocky mountains. Dept. of Meteorology, Univ. of Chicago, September.

13. 1965 a: Ageostrophische Windfelder in der hohen Tropare (Ageostrophic windfields in the high troposphere), Beitr. Phys. Atmosph. 38, 28-40.

14. 1965 b: Meteorologische Anwendungen, Abschnitt 8 an "Führer durch die Strömunglehre", 6. und 7. Auflage, (Meteorological Applications, chapter 8 in Guide through fluid mechanics, 6th and 7th editions), by L Prandtl. Braunschweig: Vieweg.

15. 1966 : Über eine Konvektionsströmung (On a convective flow), Beitr. Phys. Atmosph., 39, 235-246.

16. 1967 : Über eine Antizyklone mit starker ageostrophischer Komponente (On an anticyclone with strong ageostrophic components), Offenbach, DWD, Ann. Met.(Neue Folge), 3, 65-71.

17. 1969 : Das Feld der potentiellen Vorticity während einer Zyklonenentwicklung (Potential vorticity field during a cyclonic development) with G-M. Peter , Beitr. Phys. Atm., 42, 67-78.

Other references in this paper:

1. Bennetts D A and Hoskins B J, 1979: Conditional symmetric instability: a possible explanation for frontal rainbands. Q J R Meteorol Soc, 105, 945-962.

2. Bleck R and Mattocks C, 1984: A preliminary analysis of the role of potential vorticity in Alpine lee cyclogenesis. Contrib. Atmos. Phys., 57, 357-368.

3. Bretherton F P, 1966: Baroclinic instability and the short wavelength cut-off in terms of potential vorticity. Q J R Meteorol Soc, 92, 335-345.

4. Charney J G, 1947: The dynamics of long-waves in a baroclinic westerly current. J Meteorol, 4, 135-162.

5. Danielsen E F, 1968: Stratospheris-tropospheric exchange based on radioactivity, ozone, and potential vorticity. J Atmos Sci, 25, 502-518.

6. Eady E T, 1949: Long waves and cyclone waves. Tellus, 1, 33-52.

7. Emanuel K A, 1985: Frontal circulations in the presence of small moist symmetric stability. J Atmos Sci, 42, 1062-1071.

8. Emanuel K A, 1986: An air-sea interaction theory for tropical cyclones. Part I: steady state maintainence. J Atmos Sci, 43, 585-604.

9. Emanuel K A, Fantini M, and Thorpe A J, 1987: Baroclinic instability in an environment of small stability to slantwise moist convection. Part I: two-dimensional models. J Atmos Sci, 44, 1559-1573.

10. Helmholtz H, 1888: Über atmosphärische Bewegungen I. Sitzungsberichte Akad. Wissenschaften Berlin, 3, 647-663.

11. Hoskins B J and Bretherton F P, 1972: Atmospheric frontogenesis models: mathematical formulation and solution. J Atmos Sci, 29, 11-37.

12. Hoskins B J, 1974: The role of potential vorticity in symmetric stability and instability. Q J R Meteorol Soc., 100, 480-482.

13. Hoskins B J and West N V, 1979: Baroclinic waves and frontogenesis, Part II: uniform potential vorticity jet flows - cold and warm fronts. J Atmos Sci, 36, 1663-1680.

14. Hoskins B J, 1982: The mathematical theory of frontogenesis. Ann Rev Fluid Mech, 14, 131-151.

15. Hoskins B J,McIntyre, and Robertson A W, 1985: On the use and significance of isentropic potential vorticity maps, Q J R Meteorol Soc, 111, 877-946.

16. Hoskins B J and Berrisford P, 1988: The storm of 15/16 October 1987. A potential vorticity perspective, Weather, 43, 122-129.

17. Joly A and Thorpe A J, 1990: Frontal instability generated by tropospheric potential vorticity anomalies, Q J R Meteorol Soc, 116, 525-560.

18. Joly A and Thorpe A J, 1991: The stability of time-dependent flows: an application to fronts in developing baroclinic waves, J Atmos Sci, 47, 163-182.

19. Lanzinger A, Pichler H, and Steinacker R, 1991: ALPEX-Atlas, Case Studies of ALPEX-SOP cyclones in the Western Mediterranean. Österreichische Beiträge zur Meteorologie und Geophysik, Heft 4, 234 pp. Zentralanstalt für Meteorologie und Geodynamik, Wien.

20. Palmén E and Newton, 1969: Atmospheric circulation systems. Academic Press.

21. Pettersen S and Smebye S J, 1971: On the development of extratropical cyclones, Q J R Meteorol Soc, 97, 457-482.

22. Pichler H, Steinacker R, and Lanzinger A, 1990: Cyclogenesis induced by the Alps. Meteorol. Atmos. Phys., 43, 21-29.

23. Reed R J, 1955: A study of a characteristic type of upper-level frontogenesis. J Meteorol, 12, 542-552.

24. Rotunno R and Emanuel K A, 1987: An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a non-hydrostatic axisymmetric numerical model. J Atmos Sci, 44, 542-561.

25. Sanders F and Bosart L F, 1985: Mesoscale structure in the megalopolitan snowstorm of 11-12 February 1983, Part I: Frontogenetical forcing and symmetric instability. J Atmos Sci, 42, 1050-1061.

26. Sawyer J S, 1947: Notes on the theory of tropical cyclones, Q J R Meteorol Soc, 73, 101-126.

27. Schär C J, 1989: Dynamische Aspekte der aussertropischen Zyklogenese, PhD thesis, Eekte der aussertropischen Zyklogenese PhD thesis, ETH, Zürich, pp 241.

28. Schubert W H and Hack J J, 1983: Transformed Eliassen balanced vortex model. J Atmos Sci, 40, 1571-1583.

29. Schubert W H and Alworth B T, 1987: Evolution of potential vorticity in tropical cyclones, Q J R Meteorol Soc, 113, 147-162.

30. Shapiro M A, 1976: The role of turbulent heat flux in the generation of potential vorticity in the vicinity of upper-level jet stream systems. Mon Wea Rev, 104, 892-900.

31. Solberg H, 1928: Integrationen der atmosphärischen Störungsgleichungen, Geophys. Publ., 5, 9.

32. Tafferner A, 1991: Lee cyclogenesis resulting from the combined outbreak of cold air and potential vorticity against the Alps. Meteorol. Atmos. Phys., 43, 31-48.

33. Thorpe A J, 1985: Diagnosis of balanced vortex structure using potential vorticity. J Atmos Sci, 42, 397-406.

34. Thorpe A J, 1986: Synoptic scale disturbances with circular symmetry. Mon Wea Rev, 114, 1384-1389.

35. Thorpe A J and Emanuel K A, 1985: Frontogenesis in the presence of small stability to slantwise convection J Atmos Sci, 42, 1809-1824.

36. Volkert H, Weickmann L, and Tafferner A, 1991: The Papal front of 3 May 1987: a remarkable example of frontogenesis near the Alps. Q J R Meteorol Soc, 117, 125-150.

# Figure Captions

Figure 1:

(a) A vertical cross-section through the cyclone of 6 March 1943 at 05Z showing isentropes. Note the outlined body of increased static stability between the troposphere and stratosphere. This elevated body (Höhenkörper) is associated, by Kleinschmidt, with high PV of a value intermediate between that of the lower troposphere and the stratosphere. This figure appeared as figure 2 of (3).

(b) A three-dimensional depiction of the Höhenkörper itself above the surface synoptic chart.This appeared as figure 4 of (3).

Figure 2:

(a) Kleinschmidt's first application of the invertibility principle for a circular vortex satisfying gradient wind and hydrostatic balance. On the left in bold are the assumed contours of potential vorticity varying between 1 unit (0.3 PVU) in the lower troposphere to 8 units (2.4 PVU) in the stratosphere. Note the lentiform body of high PV in the upper troposphere representing the cause of the tropopause cyclone.

On the right is the solution of the inversion equation for tangential wind in m/s and for the isentropes. This appeared as figure 8 in (3).

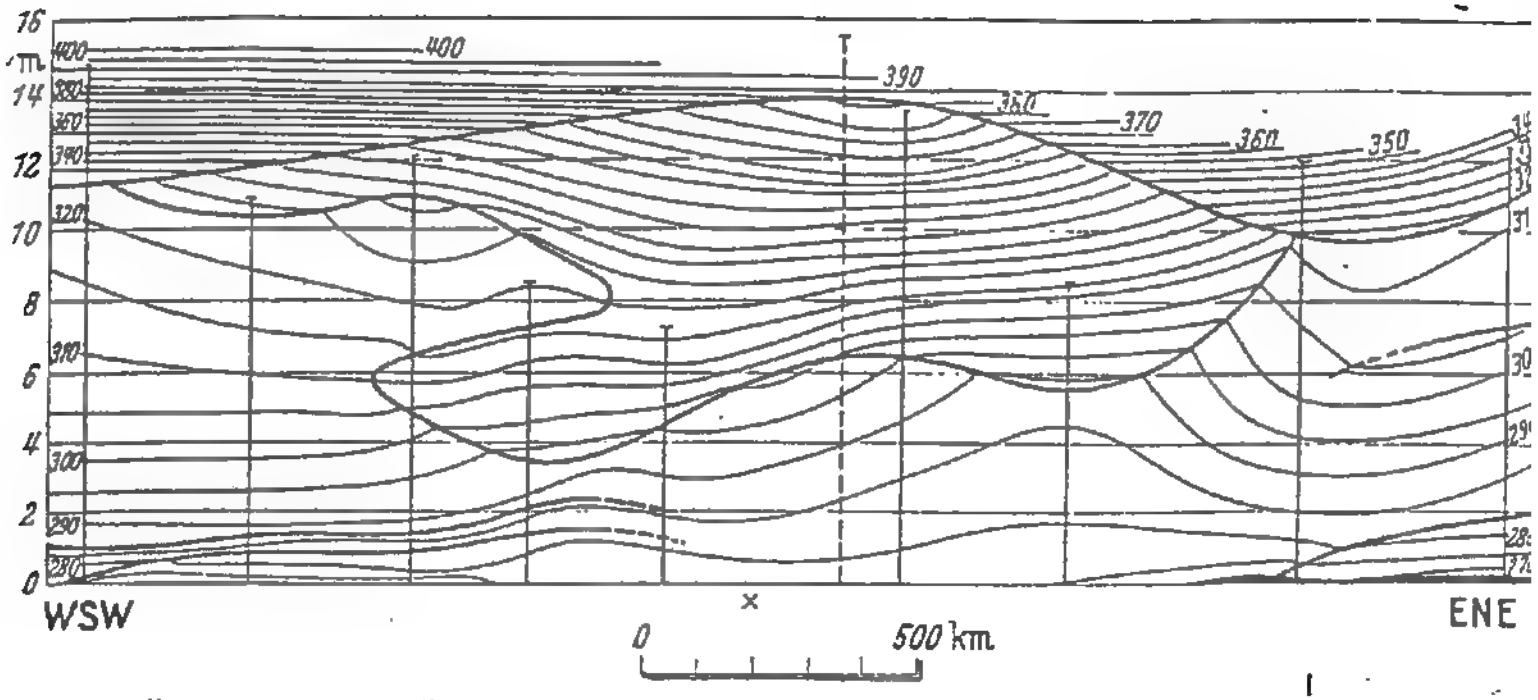
(b) The more refined solution as given in figure 23 of (10). Here the lentiform body has uniform PV of 6 times the tropospheric value. On the left are isentropes and relative pressure anomaly in mbar and on the right are isotachs in m/s.

Figure 3

A vertical cross-section through the warm front of the frontal cyclone o 16 November 1943, viewed towards the south. The plotted lines are as follows:

- thin continuous - $\theta$
- thin dashed - $\theta_w$
- thick continuous and thick dashed - discontinuous temperature gradients
- medium continuous - normal component of the geostrophic wind in m/s
- numbers in circles - normal component of the observed wind in m/s
- Roman numerals - relative humidity coded as VII = 70-79%, IX = 90-95%, X = over 95%
- arrows - absolute geostrophic vorticity vectors
- shading - cloud with rainfall shown

The cyclone is moving at 15 m/s towards the north and all winds are relative to the cyclone motion. This appeared as figure 3 in (4).


16
km
14
12
10
8
6
4
2
0
400
390
380
370
360
350
310
300
290
280
WSW
ENE
0
500 km

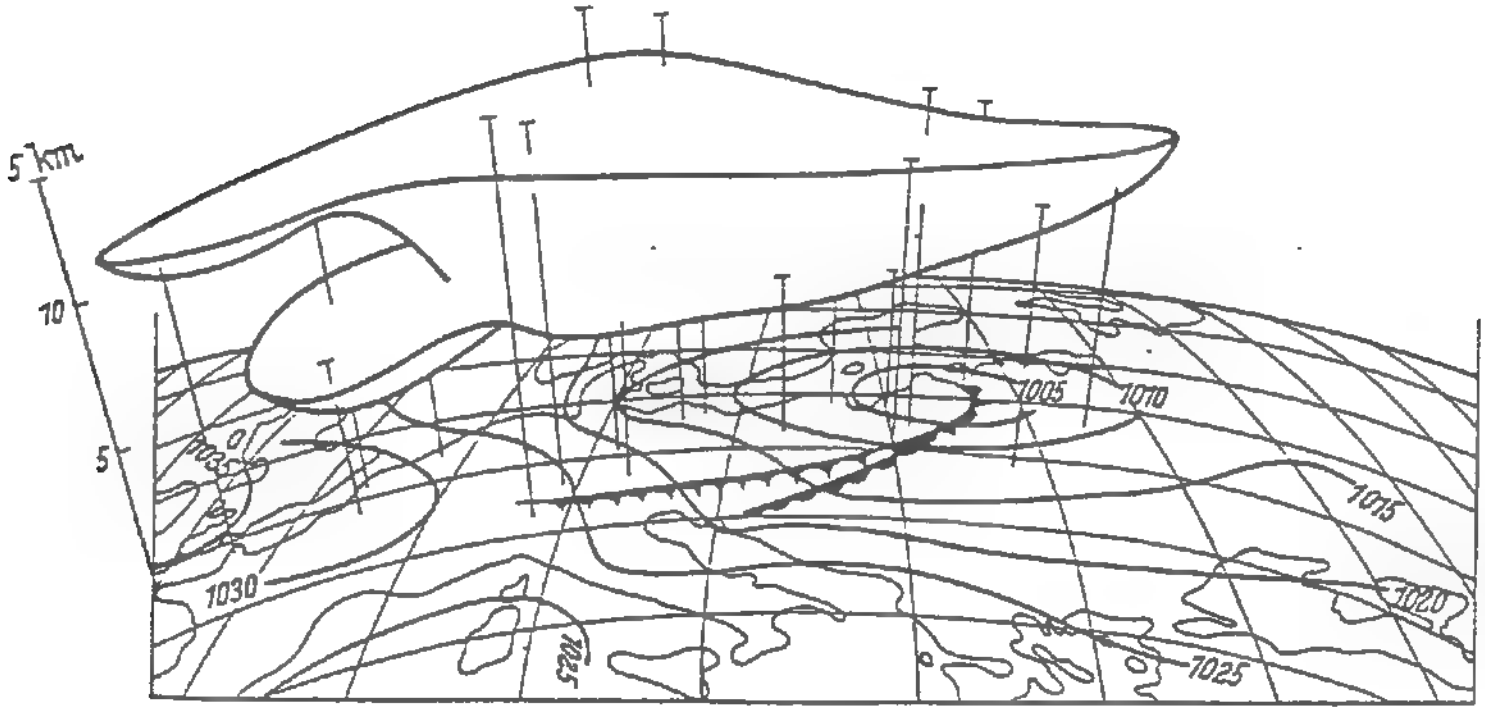
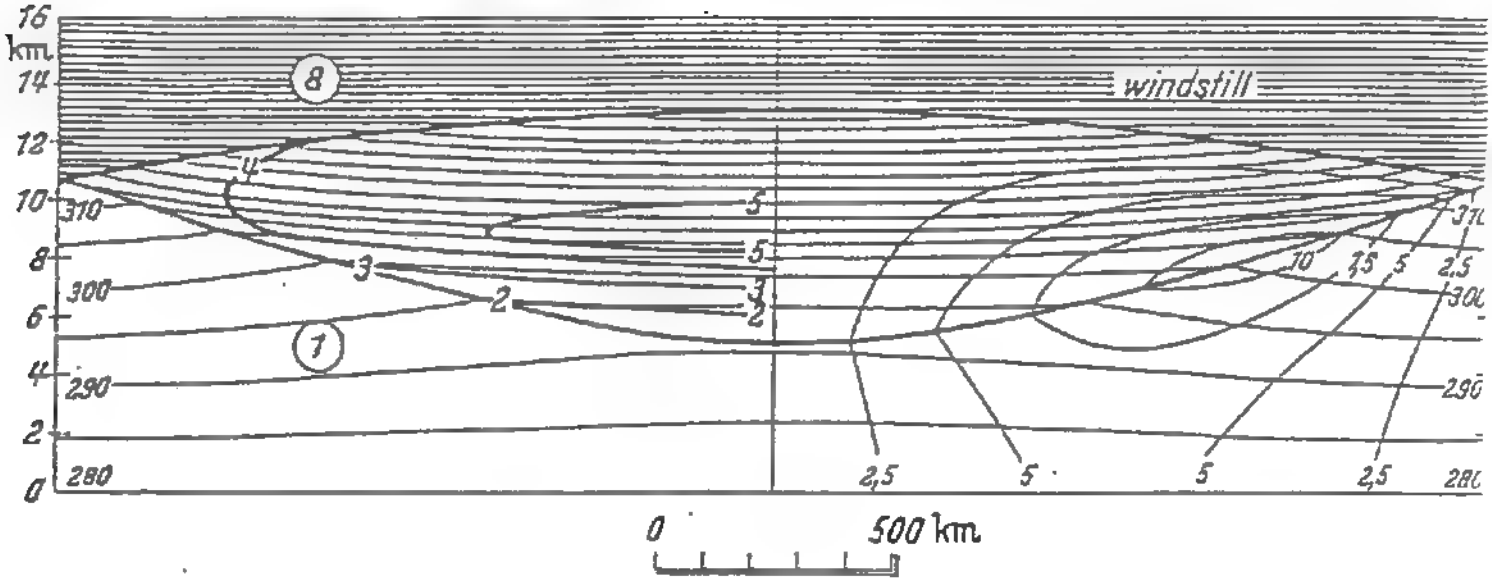

5 km
10
5
1005
1010
1015
1020
1025
1030

Fig 1


16
km.
14
12
10
8
6
4
2
0
8
windstill
4
5
5
3
3
2
2
1
310
300
290
280
10
7,5
5
2,5
2,5
5
5
0
500 km.

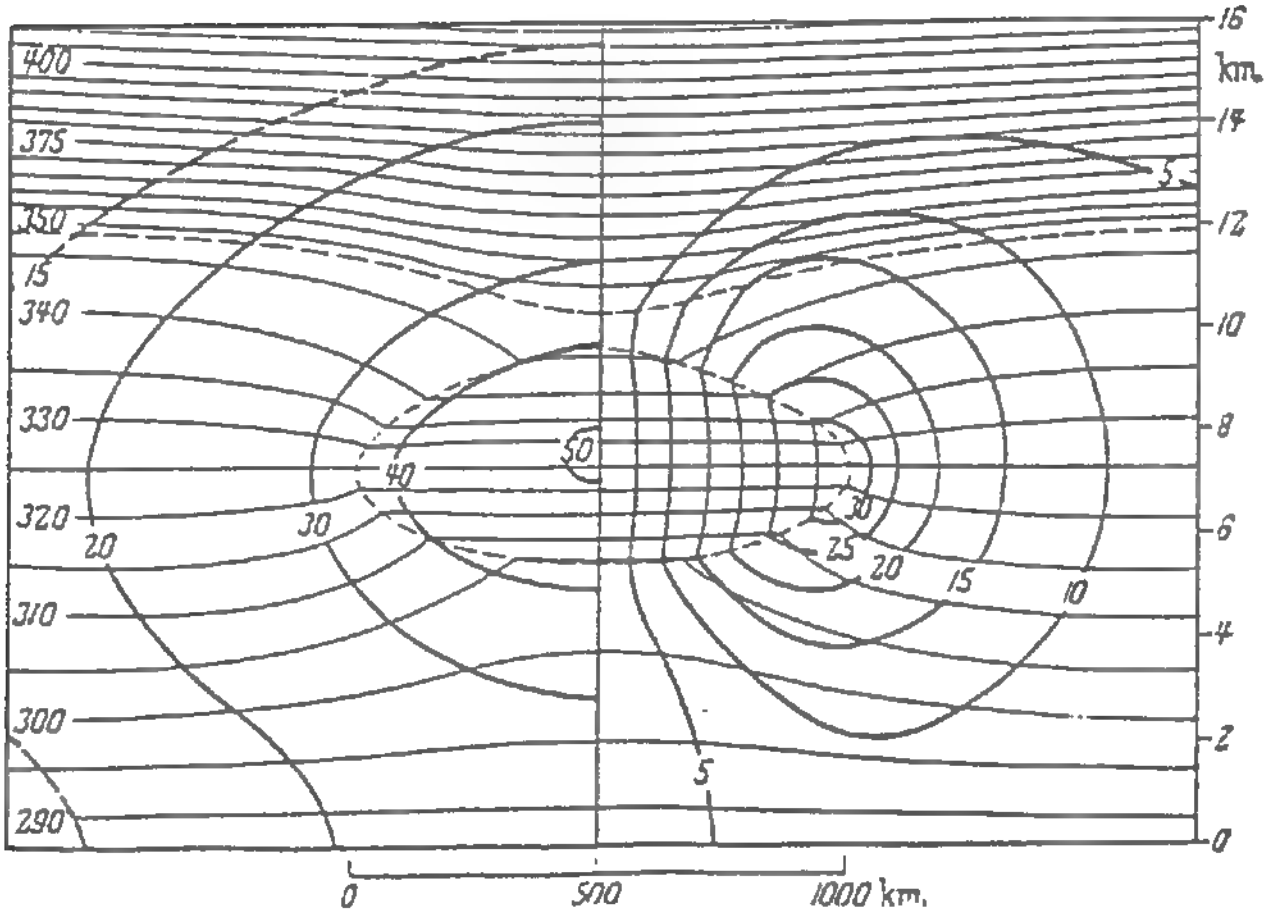

400
375
350
15
340
330
320
310
300
290
16
km.
14
12
10
8
6
4
2
0
5
50
40
30
20
30
25
20
15
10
5
0
500
1000 km.

Fig 2

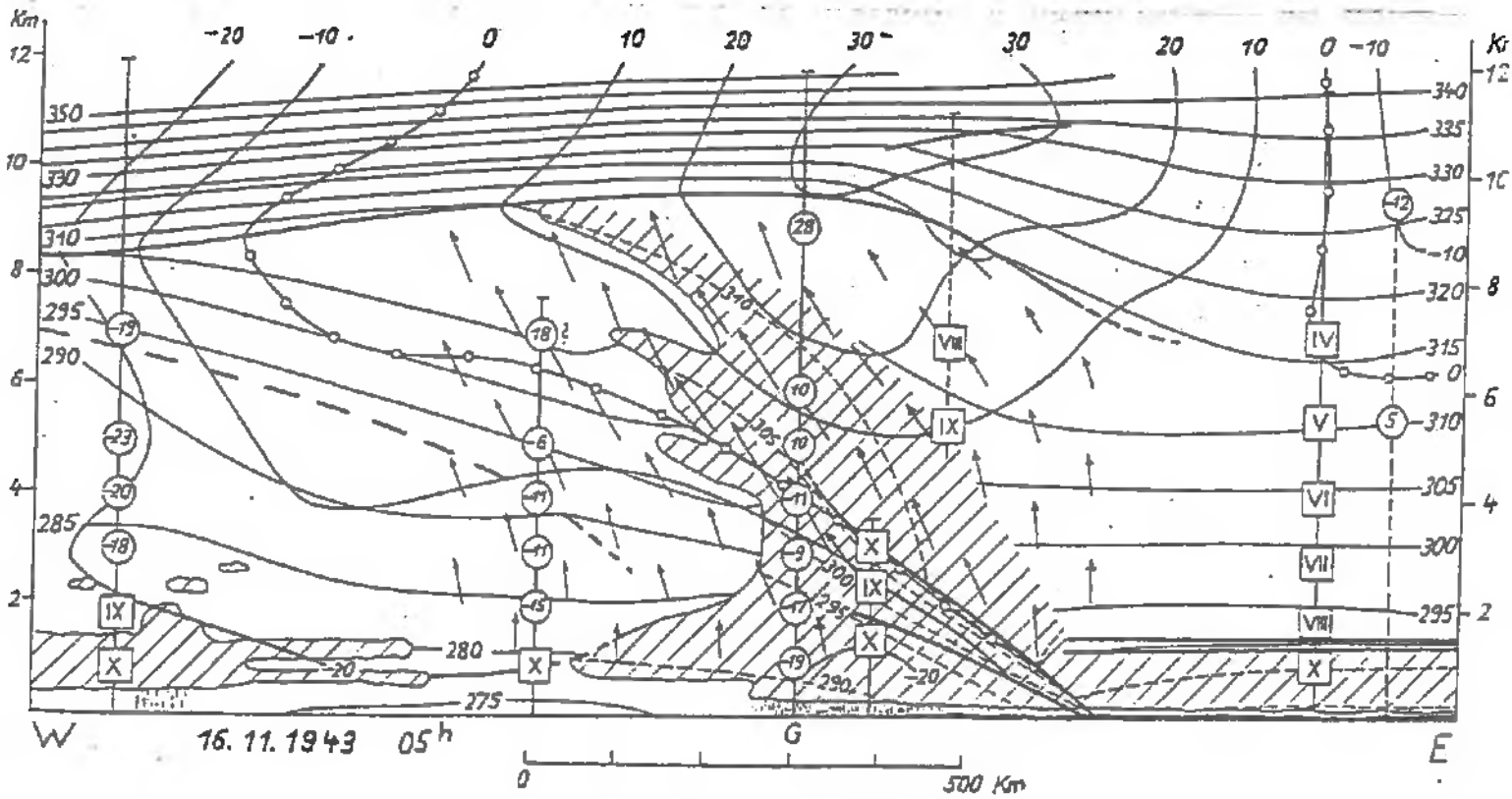

Km
12
10
8
6
4
2
-20
-10
0
10
20
30
30
20
10
0
-10
350
330
310
300
295
290
285
280
275
340
335
330
325
320
315
310
305
300
295
-10
0
W
16. 11. 1943 05h
G
E
0
500 Km

Fig 3

## CURRENT JCMM INTERNAL REPORTS

This series of JCMM Internal Reports, initiated in 1993, contains unpublished reports and also versions of articles submitted for publication. The complete set of Internal Reports is available from the National Meteorological Library on loan, if required.

1. **Research Strategy and Programme.**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS).**
   GEWEX Cloud System Science Team
   January 1993

3. **Evolution of a mesoscale upper tropospheric vorticity maximum and comma cloud from a cloud-free two-dimensional potential vorticity anomaly.**
   K A Browning
   January 1993

4. **The Global Energy and Water Cycle**
   K A Browning
   July 1993

5. **Structure of a midlatitude cyclone before occlusion.**
   K A Browning and N Roberts
   July 1993

6. **Developments in Systems and Tools for Weather Forecasting.**
   K A Browning and G Szejwach
   July 1993

7. **Diagnostic study of a narrow cold frontal rainband and severe winds associated with a stratospheric intrusion.**
   K A Browning and R Reynolds
   August 1993

8. **Survey of perceived priority issues in the parametrizations of cloud-related processes in GCMs.**
   K A Browning
   September 1993

9. **The Effect of Rain on Longwave Radiation.**
   I Dharssi
   September 1993

10. **Cloud Microphysical Processes - A Description of the Parametrization used in the Large Eddy Model.**
    H Swann
    October 1993

11. **An Appreciation of the Meteorological Research of Ernst Kleinschmidt.**
A J Thorpe
May 1992

**Met Office** Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
www.metoffice.com